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Maskless selective growth of InGaAs/InP quantum wires on (100) GaAs

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Maskless selective growth of InGaAs/InP quantum wires on (100) GaAs

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A new fabrication process to create InGaAs/InP quantum wires on (100) GaAs substrates is demonstrated. The process is based on the selectivity of the growth of InP on lines created by focused ion beam bombardment, together with the selectivity of the growth of InGaAs on the InP wires. Intense photoluminescence is observed from the wires and the emission shows clear polarization parallel and perpendicular to the wires. Cathodoluminescence images confirm that the luminescence originates from the wires. © 1997 American Institute of Physics. [S0003-6951(97)00921-2]

The theoretically predicted properties of quantum wires can be used to improve the performance of devices, such as lasers, and also to develop new device concepts based, e.g., on electron waveguiding. Consequently, a wide variety of different methods to fabricate quantum wires has emerged, including approaches based both on lithographical techniques and selective growth.¹⁻⁴ Recently it was reported that the density of InP islands deposited on (100) GaAs substrates by hydride vapor phase epitaxy (HVPE) depends strongly on the substrate off-angle, i.e., on the surface step density.⁵ This effect can be used to obtain maskless, selective growth of InP wires on planar GaAs substrates by modifying locally the surface using focused ion beam (FIB) bombardment.⁶ The process is schematically shown in Fig. 1. High resolution compositional analysis revealed that no wetting layer is present after HVPE of InP on GaAs⁷ and the nucleation seems to occur only on the implanted lines. Grooves or pre-patterned dielectric masks are not required in the fabrication process, making the fabrication of wires relatively simple. Also, precise alignment of wires on processed wafers should be possible by FIB using the available simultaneous secondary electron image. It has been demonstrated that when InGaAs, nominally lattice matched to InP, is deposited on GaAs substrate with InP islands on the surface, it grows selectively on the InP islands.⁸ In this letter we report a selective fabrication process for InGaAs/InP quantum wires on GaAs, based on the phenomena described above.

The sample preparation was as follows: $400 \times 400 \mu\text{m}^2$ fields of lines with a pitch of $3 \mu\text{m}$ were patterned by FIB on (100) GaAs wafers using 100 keV Ga^+ ions. The lines were aligned along the [011] direction. The line dose was 10^{10}cm^{-1} and the estimated diameter of the beam was 30 nm. To form the wires, InP was deposited on the implanted substrates by atmospheric HVPE.⁹ The deposition tempera-

ture was 640°C , the deposition time was 20 s and the partial pressures of InCl and PH_3 were 1.3×10^{-3} and 19.0×10^{-3} , respectively. InP was Fe-doped to a nominal concentration of $2 \times 10^{18} \text{cm}^{-3}$. The substrates were degreased, dipped in HCl and rinsed in deionized water prior to the deposition. After the formation of the wires, the substrates were transferred to a metalorganic vapor phase epitaxy

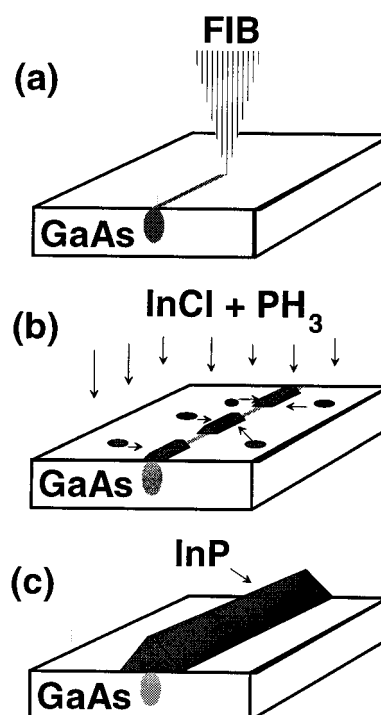


FIG. 1. Process for the selective growth of InP on GaAs shown schematically. (a) (100) GaAs substrate is bombarded by FIB. (b) InP is deposited by HVPE. The nucleation takes place on the implanted line and the nuclei act as sink to the migrating surface species. (c) The nuclei coalesce and a continuous wire is formed.

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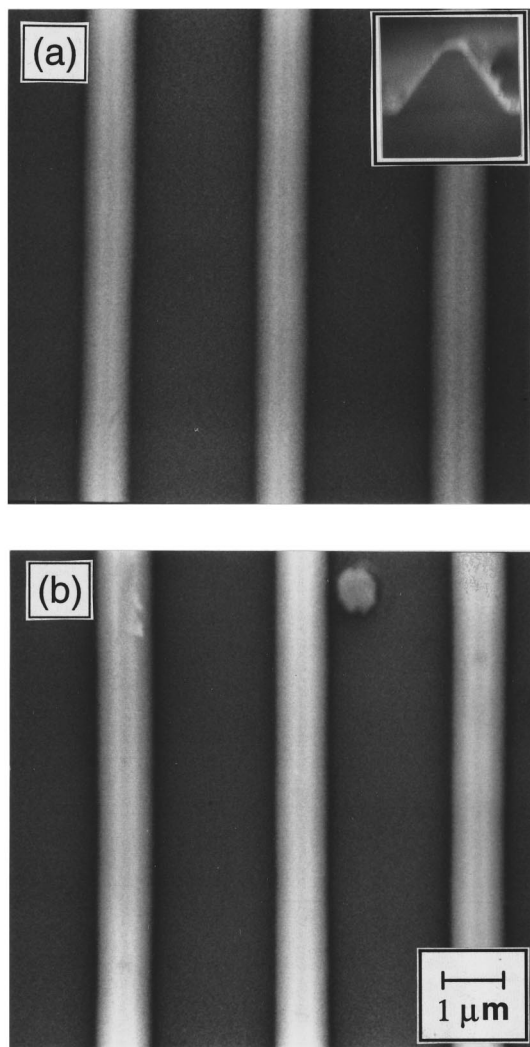


FIG. 2. Top view SEM micrographs of InP wires on GaAs (a) before and (b) after (from the sample B) the deposition of the thin InGaAs and InP cladding layers. The inset in (a) shows the cross section of a wire.

(MOVPE) reactor for the deposition of a thin layer of InGaAs and a top cladding layer of InP. Before loading, the substrates were dipped in HF:isopropanol solution, rinsed in isopropanol, and blown dry. Two samples with different layer thicknesses were grown. In sample A, a nominally 0.15-nm-thick layer of InGaAs, lattice matched to InP, was deposited at 580 °C, followed by a deposition of 10 monolayers of undoped InP. In sample B, 0.6 nm of InGaAs was deposited at 650 °C, followed by 20 monolayers of InP. MOVPE was used in the growth of InGaAs and the cladding layers because in HVPE it is difficult to control the deposition of very thin layers.

Top view scanning electron microscopy (SEM) images of InP wires, before and after the deposition of InGaAs, are shown in Figs. 2(a) and 2(b), respectively. In HVPE the growth occurred exclusively on the implanted lines. The InP wires are continuous and homogeneous in size. A cross section of a wire is shown in the inset of Fig. 2(a). The wires have (111) B side planes and a narrow, in this case about 120 nm wide, (100) top plane. This flat top can be seen also in the top view SEM images. The width of the base of the wires is about 1000 nm and the height is about 600 nm. The shape

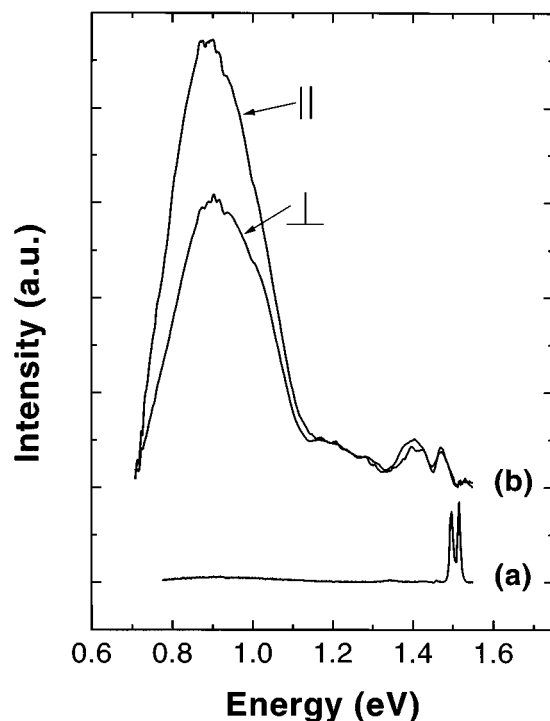


FIG. 3. Low-temperature PL spectra from (a) InP:Fe wires before the deposition of the InGaAs and InP layers by MOVPE and (b) from the sample A with polarizer parallel (\parallel) and perpendicular (\perp) to the wires.

and size are essentially unaltered after the deposition of the InGaAs and InP cladding layers. No extra islands were formed between the wires during the MOVPE growth in the sample A. In MOVPE of InP on planar (100) GaAs, islands are formed when the deposited amount of InP exceeds 2.5 monolayers.^{10,11} Here the amount of InP is 4 times the threshold for the island formation. This suggests that the deposited material migrates to and grows selectively on the InP wires. The actual structure, whether InGaAs forms top or side quantum wells or both on the InP wires, cannot be determined from the SEM images. Selectivity in the growth of InGaAs on (111) B and on (100) planes of InP has been reported,¹² and it is expected that also here the growth occurs preferentially on the top (100) plane. This would lead to a formation of about 3–4-nm-thick and 120-nm-wide InGaAs quantum wire on the top of the InP wire. In sample B the deposited amount of InGaAs and InP was about twice that in A and a few large islands appeared between the wires. One of these extra islands can be seen in the upper part in Fig. 2(b).

In Fig. 3 are shown low-temperature (14 K) photoluminescence (PL) spectra recorded before and after the deposition of the InGaAs and the cladding layers. The 488 nm-line of an Ar⁺ ion laser was used for excitation. The luminescence was dispersed through a 0.5 m monochromator and detected by a liquid nitrogen cooled Ge detector. No luminescence was observed from the Fe-doped InP wires, as can be expected when the material has a high density of deep levels. Only the emission from the GaAs substrate was detected. After the deposition of the InGaAs layer and the cladding InP layer, a broad emission appeared at around 0.9 eV, together with weaker InP related emission lines at around 1.4

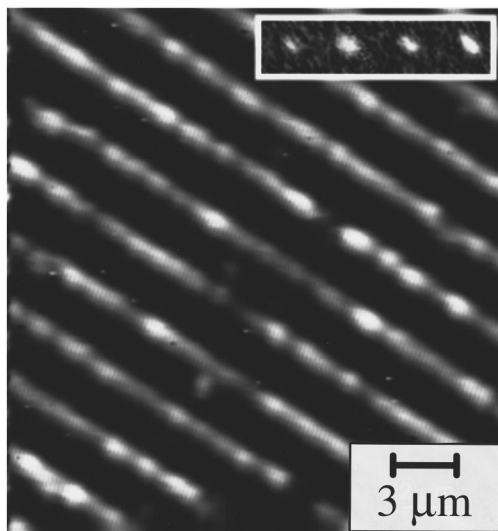


FIG. 4. Top view CL image of the sample B recorded at 25 K. The inset shows the cross-sectional image of the same sample.

eV. Figure 3(b) shows the spectra from sample A (measured with a polarizer parallel and perpendicular to the wires). The spectrum from sample B is basically similar, only the peak at 0.9 eV is a little broader. The width of the peak is a little surprising, because the wires look homogeneous with SEM. One reason for the broad emission can be the exchange of arsenic and phosphorus during the deposition of the InGaAs layer. This intermixing can be very efficient already at deposition temperatures around 600 °C and may vary along the wires.¹³

The polarization of the luminescence was measured by placing an IR-polarizer between the sample and the monochromator. The system response was calibrated using luminescence from a quantum well emitting at 0.87 eV. The emission from the wires showed a clear polarization effect. The peak intensity with a polarizer parallel to the wires is about 1.6 times higher than the intensity with the polarizer perpendicular to the wires, as shown in Fig. 3(b). This gives a polarization degree, defined as $(I_{\parallel} - I_{\perp}) / (I_{\parallel} + I_{\perp})$, of 23%, which agrees well with the calculations and experimental results reported by Ils *et al.*¹⁴ for free standing quantum wires, and suggests a one-dimensional nature of the structure.

Figure 4 shows a panchromatic cathodoluminescence (CL) image from the sample B recorded at 25 K. The inten-

sity of the emission varies along the wires. By selecting different spectral regions within the broad PL peak, fluctuations can be observed along the wires, suggesting that the thickness and/or composition are not constant. The image confirms that all the light emitted from the sample comes from the wires.

In summary, a new fabrication process to create InGaAs/InP quantum wires on (100) GaAs substrates is proposed and demonstrated. The process is based on the selectivity of the growth of InP on lines created by focused ion beam bombardment together with the selectivity of the growth of InGaAs on InP wires on GaAs. Intense photoluminescence is observed from the wires and the emission shows clear polarization between luminescence parallel and perpendicular to the wires. Cathodoluminescence images confirm that the luminescence originates from the wires.

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